FLUX COMPRESSION GENERATOR DEVELOPMENT AT THE AIR FORCE RESEARCH LABORATORY

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Abstract

The Air Force Research Laboratory (AFRL) maintains an extensive capability for the design, analysis, construction and testing of explosive pulsed power (EPP) components. Three flux compression generators (FCGs) were designed as part of an EPP technology development effort sponsored by AFRL and the Defense Advanced Research Projects Agency (DARPA). A secondary-stage, high-current FCG was designed to deliver 10 MA into a nominal load inductance of 80 nH from an initial generator inductance of 1.6 µH that is seeded with 1 MA. We have also developed a coaxial FCG to deliver more than 20 MA into a 2 nH load. The initial flux in the coaxial chamber (60 nH at 1.5 MA) is compressed uniformly using a copper armature, which is simultaneously initiated using a slapper detonator. Either of these two FCGs can be seeded with a third generator design: a high-gain, helical FCG. This model serves as our workhorse generator capable of delivering 2 MA into a 0.5 µH inductive load. It has also been operated into load inductances ranging from 0.1 to 2.0 µH with comparable flux delivery. All experiments are conducted on an explosive test range located on Kirtland Air Force Base [1]. The design effort is supported by powerful computer modeling using CAGEN [2], CALE and MACH2. Design features for all three FCGs are presented in this paper with results from recent explosive tests.

I. INTRODUCTION

There is extensive interest in FCGs for a variety of applications [3]. To add to this body of work we have developed three generator designs at AFRL and they are listed in Table 1. The MCGJ is a high-gain generator that can be used to seed the MCGB and MCGC. It has been operated into a range of load inductances with a flux delivery of about 1 Wb. The MCGB is a low-gain, high-output-current generator using a 16-conductor, helical winding. The last design is the MCGC which is a coaxial generator that uses simultaneous axial initiation to compress the flux.

Table 1. Recent FCG designs developed at AFRL.

Model	Type	Inductance	Output
MCGJ	Helical	300 µH	1.9 MA into 0.55 µH
MCGB	Helical	1.7 µH	10 MA into 80 nH
MCGC	Coaxial	62 nH	20 MA into 2.1 nH

II. DESIGN AND TESTING

Once the generator design requirements are defined, the process begins with a parametric study of stator designs using CAGEN [2]. This code has proved to be an excellent predictor of generator performance. When the stator design is complete, the supporting hardware is designed as a three dimensional model using SolidWorks®. The models created can be ported to electromagnetic analysis packages such as QuickField®, FlexPDE® and COSMOS-EM®. Advanced magnetohydrodynamic (MHD) computations can also be performed using CALE and MACH2. These tools allow rapid prototyping to a test article.

All generators are fabricated in-house and the tests are conducted at the Chestnut site at Kirtland AFB [1]. Generator currents are usually measured with Rogowski coils. When practical, these sensors are backed up with Faraday Rotation measurements. At higher field intensities, such as in MCGC, Bdot probes are used. All data is recorded using digitizing oscilloscopes.

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III. HELICAL DESIGNS

The MCGJ shown in Figure 1 is a general pupose, megjoule-class FCG for research purposes [4]. The magnetic flux is compressed using a 15 cm diameter explosive armature that is cast with PBXN-110. The expansion ratio of the armature is a conservative 1.7 to the stator ID of 26 cm. The stator is wound with two parallel conductors and has an initial inductance of 300 μH.

Figure 1. Assembly of MCGJ ready for test

The di/dt recorded for a typical shot is plotted in Figure 2. The corresponding peak output voltage is about 50 kV. The measured current is shown in Figure 3. All data are plotted with respect to time after crowbar. A summary of the generator performance for different load sizes and seed currents is provided in Table 2.

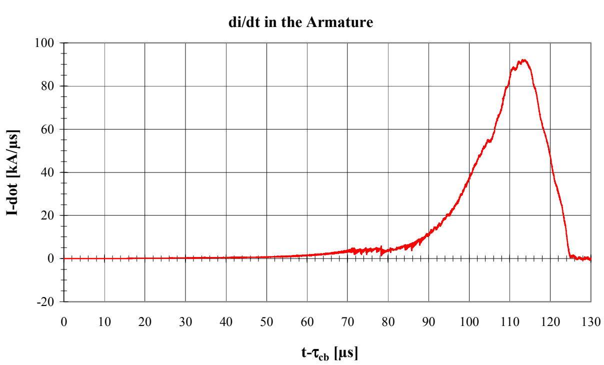


Figure 2. Typical measured Idot for the MCGJ

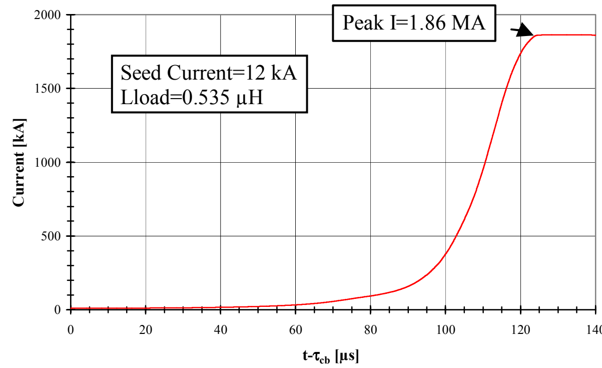


Figure 3. Typical output current for the MCGJ.

Table 2. Performance of the MCGJ.

Shot#	Load Inductance	Seed Current	Output Current
00-6-02	0.545 μH	12.1 kA	1.86 MA
02-6-01	0.240 μH	12.2	2.75 MA
03-6-01	0.922 μH	6.08	992 kA
03-6-02	1.96 μH	6.00	633 kA

The high current MCGB helical generator is shown in Figure 4. The dimensions of the armature and stator are identical to those of the FCGJ. The stator is wound with sixteen #2 AWG conductors at a constant pitch. The initial inductance of the generator is 1.7 μH. Careful engineering of the output connections was necessary to handle the output current of 10 MA. Concrete tamping around the end of the stator is used to prevent gross movement of the conductors. The output current of the MCGB is plotted in Figure 5.

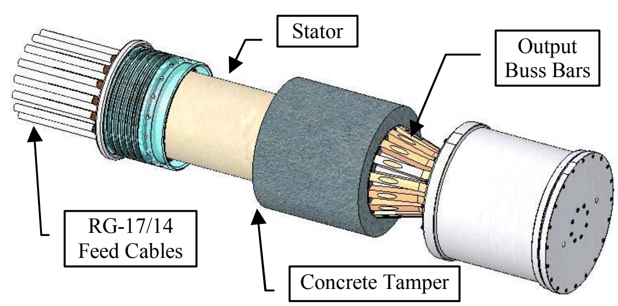
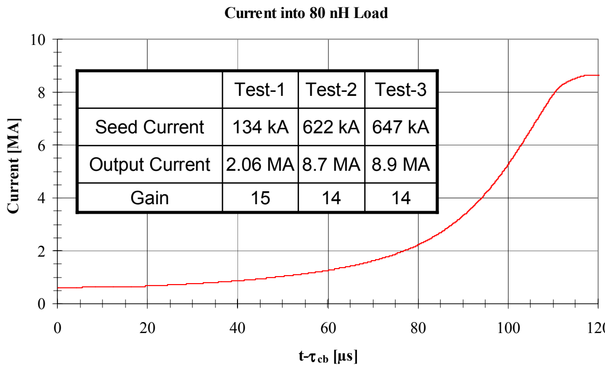


Figure 4. Mechanical Design of the MCGB



	Test-1	Test-2	Test-3
Seed Current	134 kA	622 kA	647 kA
Output Current	2.06 MA	8.7 MA	8.9 MA
Gain	15	14	14

Figure 5. MCGB Ouput current plotted with the code prediction.

IV. COAXIAL FCG DESIGN

The MCGC coaxial generator is shown in Figure 6. This design uses a fully-annealed copper armature with an outer diameter of 75.2 mm. The active length of the armature is 44 cm and it is cast with PBXN-110 under vacuum. The simultaneous initiation of the explosive is achieved using two 24-point slapper detonation cables, which were fabricated by Los Alamos National Laboratory.

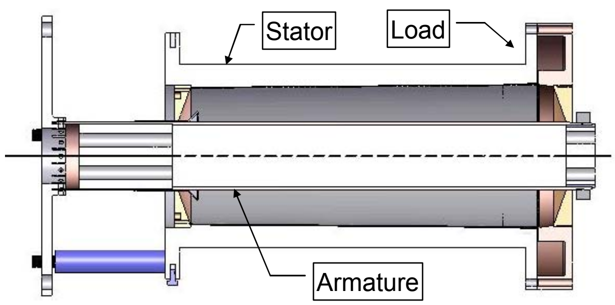


Figure 6. Cut-away view of the MCGC design.

The armature design was assembled and tested to measure any deviation from an ideal cylindrical expansion. An axial array of piezoelectric pins (Figure 7) was used to measure the Time-Of-Arrival (TOA) at a fixed radius corresponding to the stator. The data from these pins are plotted versus the axial position in Figure 8. The data is fit to a sinusoidal curve with a period of 2.83 mm and a ripple of 1.8 mm peak-to-valley at full expansion.

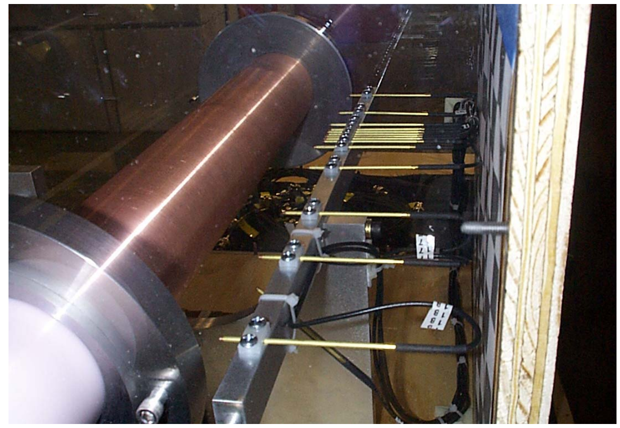


Figure 7. Axial TOA pin array for the MCGC armature test.

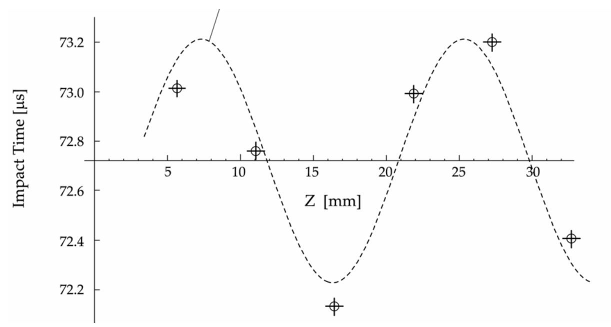


Figure 8. Impact time fit to a sinusoidal curve to estimate the ripple.

In a similar manner, an azimuthal pin array (Figure 9) was used to measure the cylindricity of the armature expansion. The data, plotted in Figure 10, can be fit to an ellipse with maxima at 76.2 mm and 78.8 mm. Therefore, the expansion is out-of-round by 2.6 mm. The arrival was uncharacteristically late at the top of the hemisphere detonators (90°) versus at the edge of the cables (0° and 180°). While not ideal, the armature performance is acceptable for this generator design. The output current measured for the MCGC is shown in Figure 11.

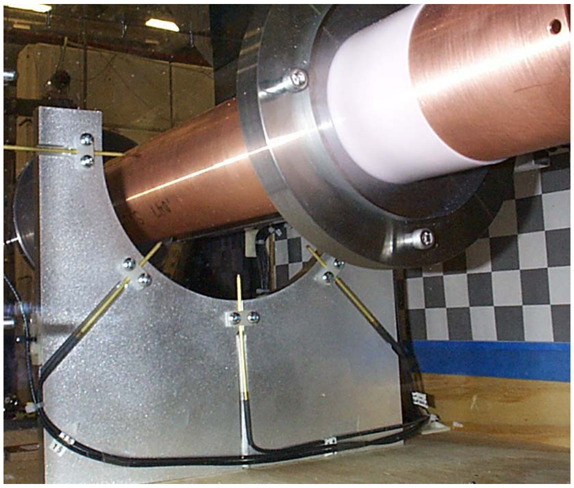


Figure 9. Radial TOA pin array used on the armature test.

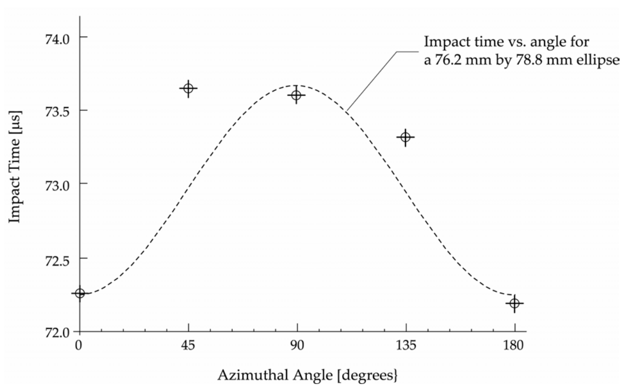


Figure 10. Time of arrival data plotted versus angular location and fit to an ellipse.

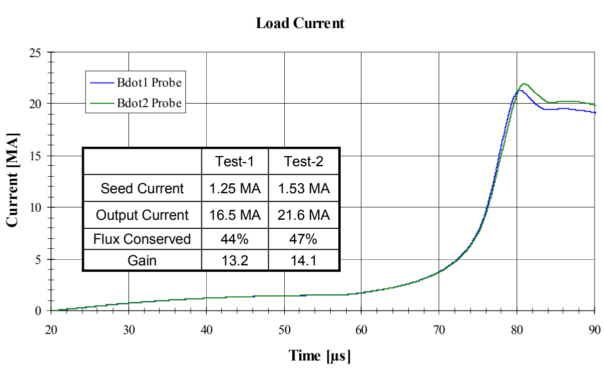


Figure 11. Output current measured for the second MCGC test plotted versus time.

V. SUMMARY

We have assembled a team to design, build and test explosive pulsed power generators at AFRL. This team makes use of extensive modeling tools throughout the design process to maximize performance while minimizing the development time. Three new designs have been developed to provide generation over a wide range of currents and energies.

VI. REFERENCES

[1] J. Parker, *et al.*, "The Explosive Pulsed Power Test Facility at AFRL," 15th International Pulsed Power Conference, June 13-17, 2005.

[2] J. B. Chase, *et al.*, "Benchmarking the Care'n Co. Flux Compression Generator Code, CAGEN, Implementing the Kiuttu Contact Resistance Model," 15th International Pulsed Power Conference, June 13-17, 2005.

[3] A. A. Neuber and J. C. Dickens, "Magnetic Flux Compression Generators," Proceedings of the IEEE, Vol. 92, No. 7, pp. 1205-1215, July 2004.

[4] M. Lehr, *et al.*, "Helical Explosive Flux Compression Generator Research at the Air Force Research Laboratory." 12th International Pulsed Power Conference, June 27-30, 1999, Digest of Technical Papers, Vol. 1, pp. 339-342.

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